Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 5 (2013) 100 – 103

www.elsevier.com/locate/procedia

The First CIRP Conference on Biomanufacturing

Robotic Ultrasound Guidance by B-scan Plane Positioning Control

Shinya Onogi*, Toshio Yoshida, Yuki Sugano, Takashi Mochizuki, Kohji Masuda

Tokyo University of Agriculture and Technology, 24-2 Naka-cho, Koganei, Tokyo 184-8588, Japan

* Corresponding author. Tel.: +81-42-388-7434. *E-mail address*: sonogi1@cc.tuat.ac.jp.

Abstract

Ultrasound is indispensable imaging modality for clinical diagnosis such as fetus assessment and heart assessment. Moreover, many ultrasound applications for image guided procedures have been proposed and attempted because US is less invasive, less cost, and high portability. However, to obtain US images, a US imaging probe has to be held manually and contacted with a patient body. To address the issue, we have proposed a robotic system for automatic probe scanning. The system consists of a probe scanning robot, navigation software, an optical tracking device, and an ultrasound imaging device. The robot, that is six degrees of freedom, is composed of a frame mechanism and a probe holding mechanism. The frame mechanism has six pneumatic actuators to reduce its weight, and the probe holding mechanism has one DC motor. The probe holding mechanism is connected with the pneumatic actuators using wires. Moreover, the robot can control the position and orientation of the B-scan plane based on the transformation between an optical tracker attached to the US probe and the B-scan plane. The navigation system, which is connected with the tracking device and an US imaging device via a VGA cable, computes the relative position between the positions of a therapeutic tool and the B-scan plane, and sends it to the robot. Then the position of the B-scan plane can be controlled based on the tool position. Also, the navigation system displays the plane with a texture of an actual echogram and a tool model three-dimensionally to monitor the relative position of the tool and the B-scan plane. To validate the basic system performance, phantom tests were conducted. The phantom was made of gelatin and poly(ethylene glycol). In the tests, the needle was inserted into the phantom, and the B-scan plane was controlled to contain a tracked needle in real-time. From the results, the needle was continuously visualized during needle insertion. Therefore, it is confirmed that the system has a great potential for automatic US image guided procedures.

Selection and/or peer-review under responsibility of Professor Mamoru Mitsuishi and Professor Paulo Bartolo

Keywords: Pneumatic actuator; wire-driven robot; US probe scanning; navigation system; ultrasound guidance

1. Introduction

Medical imaging modalities, such as Computer Tomography (CT), Magnetic Resonance Imaging (MRI), and Ultrasound (US), are indispensable technology for diagnosis at present. Moreover, the imaging modalities are also applied to intra-operative procedures to monitor surgical processes for safety. That is referred to an image guidance. CT and MRI provide true 3D images (volume) because those have the base coordinates. However, CT and MRI are high-cost and needed a space for placement. Meanwhile US has been used as a widely popular image guidance modality, because it is low latency, convenient to use in a conventional operating room, and inexpensive compared to CT and MRI. However, one of technical issues of US is that a technician has to hold a US imaging probe and scan on surface of patients. That causes following issues: US technicians may develop musculoskeletal disorders for technicians and three-dimensional positional information of images is not provided. Therefore, automatic scanning with 3D positional information is expected similar to CT and MRI.

A direct solution for the issue is robotic probe scanning system. Several robots for remote US diagnosis or automatic scanning have been reported [1-3].These studies enable to position a US probe accurately; however, these robots are large size in dimension, heavyweight, and quite rigid structure to bear self-

Selection and/or peer-review under responsibility of Professor Mamoru Mitsuishi and Professor Paulo Bartolo
doi:10.1016/j.procir.2013.01.020

weight. These points should be considered as risk factors for clinical use. Meanwhile, some robots mounted on a patient have also been proposed: e.g. [4] for tele-echography. However, the robot is still heavy, 2.2 kg, for mounting use and does not have six degrees-of-freedom. Moreover, the mechanism does not have backdrivability since the robot was composed of electric motors and harmonic drives. Thus, lightweight and high backdrivable robots are better for clinical purpose. Meanwhile, these robots do not provide accurate 3D positional information of acquired images because they control a tip of a US probe which is not equivalent with position and orientation information of a B-scan plane.

To address the issue, accurate 3D position and orientation of a B-scan plane are indispensable. General approach is tracking an imaging probe with a tracking device. In this case, a fixed transformation between the echogram plane and the tracking device is obtained by US calibration [5-8]. When the transformation is applied to the robot control, the robot can manipulate a B-scan plane rather than the probe. For this purpose, we have developed the robot, which controls a position of a B-scan plane [9].

In this study, the robot was applied to a navigation system to monitor a therapeutic area automatically. The basic performance of the US navigation system was evaluated by a phantom test.

2. Materials and Methods

2.1. Probe Scanning Robot

The robot with 6 degrees of freedom consists of two parts: a frame mechanism and a probe holding mechanism. The frame mechanism was composed two aluminum rings with 240 mm diameter, six aluminum cylinders with 10 mm diameter and 167 mm length, and six Mckibben pneumatic actuators. The probe holding mechanism has a DC motor and is connected with the respective pneumatic actuators using wires. Therefore, the probe holding mechanism has 6-dof. The whole weight excluding a US probe is 920 g.

To manipulate a B-scan plane position, the transformation matrix between a US probe and a B-scan plane is required. Obtaining the transformation is generally referred as US probe calibration or US calibration. Let F, R, and E be the frame coordinate systems of the frame mechanism, the probe holding mechanism, and the B-scan plane, respectively. When a target B-scan plane position ${}^{F}T_{E}$ is given, the target probe position ${}^{F}T_{R}$ is obtained as:

$$ {}^{F}T_{R} = {}^{F}T_{E}\,{}^{E}T_{R}. \quad (1)$$

where ${}^{E}T_{R}$ is the US calibration matrix. From the target probe position ${}^{F}T_{R}$, the target wire lengths are computed by the inversed kinematics of the robot.

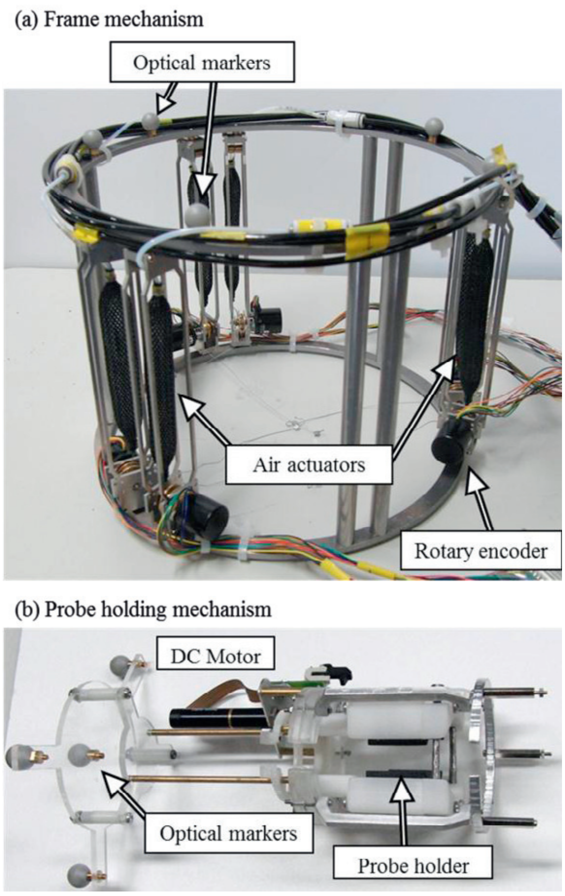

Fig. 1 Mckibben pneumatic actuator

2.2. Navigation Software

We integrated between an in-house navigation system and the probe scanning robot for the guidance of ultrasound images. Target positions of the B-scan plane are generated from the navigation information, positions of a tracked tool and a B-scan plane.

The navigation system consists of navigation software, the probe scanning robot, and an optical tracking device (Polaris Spectra, Norther digital). The software was developed by C++ language (Visual Studio 2010, Microsoft) using visualization tool kit (VTK, Kitware).

To monitor a needle insertion process, the B-scan plane has to be manipulated to contain the needle in the plane. So, the navigation software computes the transformation between the needle and the B-scan plane by following equation.

$$ {}^{E}T_{N} = {}^{E}T_{F}\,{}^{F}T_{N}. \quad (2)$$

where E is the echogram coordinate system, N is the needle coordinate system, and F is the frame coordinate system. The needle coordinate system was defined as follows: the origin is the tip position and the z-axis is the tool axis. Let a translation vector (p_x, p_y, p_z) be the translation component of ${}^{E}T_N$. Then, the motion of the B-scan plane is given by the following steps.

1 Translate the B-scan plane to contain the needle tip in the plane.

$$\mathrm{Trans}(0, 0, p_z). \tag{3}$$

where Trans(x, y, z) is an abbreviation of a translation matrix of 4 by 4.

2 Rotate the B-scan plane around the axis, which direction is y-axis of the plane and passes through the needle tip, to contain the needle axis in the plane.

$$\mathrm{Trans}(p_x, 0, 0)\mathrm{RotY}(\theta)\mathrm{Trans}(-p_x, 0, 0). \tag{4}$$

$$\theta = \sin^{-1}(\overrightarrow{n_E} \times \overrightarrow{z'_N}). \tag{5}$$

where RotY(θ) is an abbreviation of rotation matrix around y-axis, $\overrightarrow{n_E}$ is the normal vector of the B-scan plane (0, 0, 1), and z'_N is the projection of the needle axis to xz-plane. Finally, the target position of the B-scan plane ${}^{F}T'_E$ is obtained as

$$ {}^{F}T'_E = {}^{F}T_E\ \mathrm{Trans}(p_x, 0, p_z)\ \mathrm{RotY}(\theta)\mathrm{Trans}(-p_x, 0, 0). \tag{6}$$

According to the above formula, the robot automatically manipulates the position of the B-scan plane to contain the needle in the plane, shown in Fig. 2.

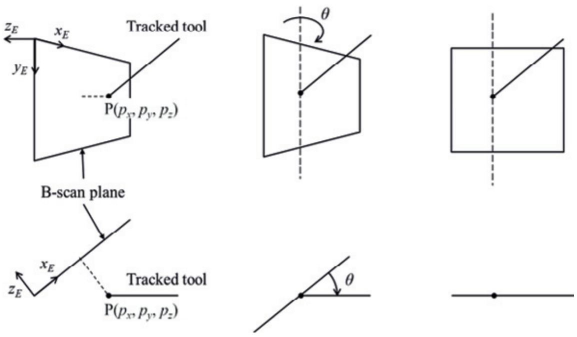

Fig. 2. B-scan plane motion to contain the therapeutic area and path in the plane.

To validate the basic performance of the integrated navigation system, needle insertion tests using a phantom were conducted. In the test, a tracked needle as a therapeutic tool and a phantom consisting of poly(ethylene glycol), agar, and gelatin, were used. The phantom contained a metal ball with 11 mm diameter as a target (Fig. 3). Also, the whole experimental setup is shown in Fig. 4.

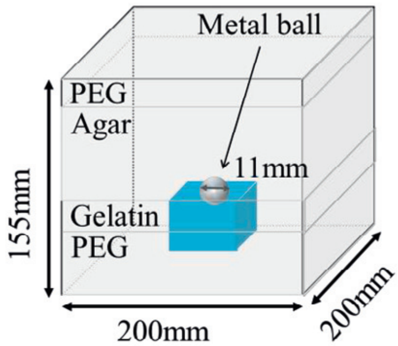

Fig. 3. Phantom for the needle insertion guidance.

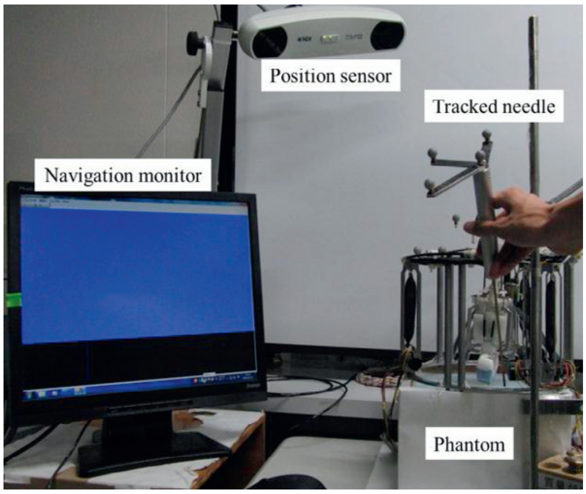

Fig. 4 Experimental setup for the needle insertion tests.

3. Results

Using the integrated navigation system and the phantom, needle insertion tests were conducted. Highlight images of the navigation screenshots during needle insertion are shown in Fig. 4.

Characteristically, the needle insertion process could be monitored during the tests by the automatic probe manipulation. According to the tracking device measurement, in-plane accuracy was obtained. The translational errors between the needle tip and the plane were 2.22 ± 11.6 mm. The angular errors between the needle axis and the plane were 3.88 ± 3.69 degree.

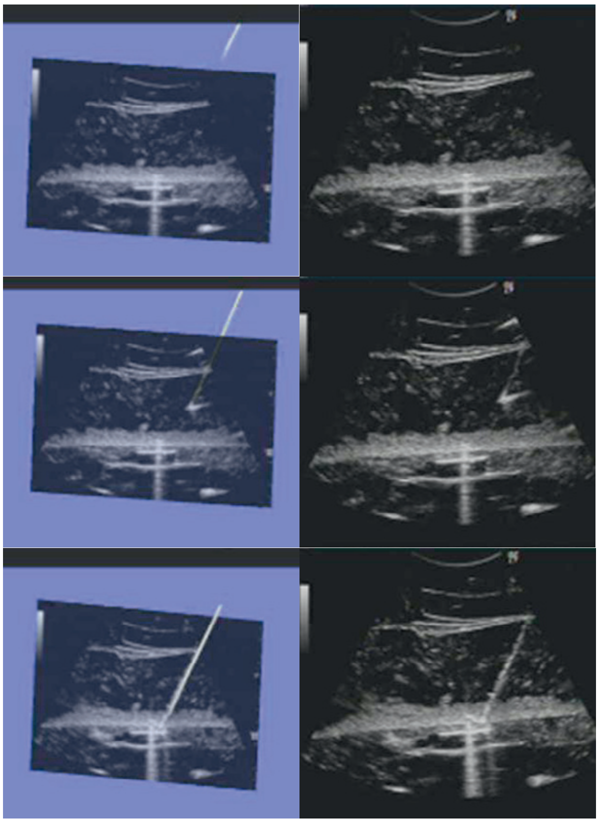

Fig. 4. The navigation views and echograms of the needle insertion test. Left: three dimensional views of the B-scan planes and the tracked needle. Right: raw echograms.

4. Conclusions

In this paper, we proposed the navigation system using the probe scanning robot and the B-scan plane positioning control. The robot can manipulate the B-scan plane of a US probe. Using the plane positioning control, we developed the navigation system to monitor therapeutic processes automatically. From the phantom tests, the needle insertion process could be observed in real time. The positioning accuracies were 2.22 mm and 3.88 degree. The results demonstrate that the system has great potential for the US guidance. In future work, positioning errors should be reduced less than 2.0 mm and 2.0 degree.

Acknowledgements

This research was supported by the Japan Society for the Promotion of Science (JSPS) through the Funding Program for Next Generation World-Leading Researchers (NEXT Program).

References

[1] Janvier, M.A., Durand, L.G., Roy Cardinal, et al, “Performance evaluation of a medical robotic 3D-ultrasound imaging system,” *Med. Image Anal.* vol. 12, pp. 275-290, 2008.

[2] Nakadate, R., Uda, H., Hirano, H., et al, “Development of Assisted-Robotic System Designed to Measure the Wave Intensity with an Ultrasonic Diagnostic Device,” in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2009, pp. 510-515.

[3] Abolmaesumi, P., Salcudean, S.E., Zhu, W.H., DiMaio, S.P., Sirouspour, M.R., “A User Interface for Robot-Assisted Diagnostic Ultrasound ,” in *Proc. IEEE Int. Conf. on Robot. Autom.*2001, 1549-1554.

[4] Ito, K., Sugano, S., Iwata, H., “Portable and Attachable Tele-Echography Robot system: FASTele.” in *Proc. Annual Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, 487-90.

[5] E. Boctor, A. Viswanathan, M. Choti, R. H. Taylor, ”A novel closed form solution for ultrasound calibration,” in *Proc. IEEE International Symposium on Biomedical Imaging*, vol. 1, pp. 527-530, 2004.

[6] H. Zhang, F. Banovac, A. White and K. Cleary, ”Freehand 3D ultrasound calibration using an electromagnetically tracked needle,” in *Proc. SPIE 6141*, 61412M, 2006.

[7] E. L. Melvær, K. Morken, and E. Samset, ”A motion constrained crosswire phantom for tracked 2D ultrasound calibration,” *Int. Journal of Computer Assisted Radiology and Surgery*, vol. 7, pp. 611-20, 2011.

[8] S. Onogi, Y. Sugano, T. Yoshida, K. Masuda, “An Accurate Calibration Method of Ultrasound Images by Center Positions of a Metal Ball,” in *Proc. Annual Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2012, 468-471.

[9] T. Yoshida, S. Saito, S. Onogi, K. Masuda, “Position Control of Echogram Plane by Probe Scan Mechanism using Pneumatic Actuators,” in *Proc. Int. Conf. Computer Assisted Radiology and Surgery*, vol. 7 suppl. 1, S358, 2012.